Forest Ecology and Management 264 (2012) 37–50

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Cradle-to-gate inventory of wood production from Australian softwood plantations and native hardwood forests: Embodied energy, water use and other inputs

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ARTICLE INFO

Article history:
Received 26 May 2011
Received in revised form 9 September 2011
Accepted 10 September 2011
Available online 1 November 2011

Keywords:
Forestry
Life cycle inventory
Wood products
GHG mitigation
Water use
Harvesting and transport

ABSTRACT

With increasing focus on the environmental impacts of alternative land uses and materials, there is a growing need to produce accurate and verifiable life cycle inventories for forestry. A cradle-to-gate inventory was produced for wood from softwood plantations and hardwood native forests across Australia, covering all operations involved in forest establishment, management and harvesting and including transportation of logs and chips to processing facilities. The inventory was primarily based on data provided by forest growers, managers and contractors across seven case study regions. The SimaPro model was used to combine the different operations, and to account for upstream processes associated with the production of fuel and materials used. Forest products included high- and low-grade sawlogs, pulplogs, woodchips and other logs. Inputs were expressed in terms of m^3 product and were allocated to products on an economic basis. Key inputs for wood from softwood plantations included land (0.06 ha m^{-3}), water (0.12 ML m^{-3}), diesel (172 MJ m^{-3}) and fertiliser (0.3 kg N m^{-3}, 0.2 kg P m^{-3}, 0.06 kg K m^{-3}). Key inputs for wood from native forests included land (0.28 ha m^{-3}), water (0.38 ML m^{-3}) and diesel (355 MJ m^{-3}). The largest contributors to total energy use were log haulage (46% for softwood and 45% for hardwood) and harvesting and chipping (29% for softwood and 44% for hardwood). However, the total amount of energy used in the forestry production process (293 MJ m^{-3} for plantation softwood and 527 MJ m^{-3} for native hardwood) was very small relative to the net energy content of the logs harvested, representing just 4% of that in an average plantation softwood log and 6% of that in an average native hardwood log. Thus, forest products have low embodied energy and have strong potential for greenhouse gas mitigation when used for bioenergy.

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1. Introduction

With growing awareness of the need to improve the environmental performance of products, Life Cycle Assessment (LCA) is increasingly being seen as a practical method for comparing the impact of alternative materials or processes in a consistent manner. Life cycle inventories (LCIs) and cradle-to-gate inventories (CGIs) provide the raw data for this analysis with the former tracking a product from its initial production to its final disposal and the latter tracking a product through just a portion of its lifespan.

The capacity of forests to sequester carbon, act as a source of renewable materials and energy and provide a range of other environmental services and benefits has seen increasing focus on the development of LCIs for the forest industry (e.g. Hillier and Murphy, 2000; Jungmeier et al., 1999; Kosir, 1999). Forestry CGIs have been developed or adapted for countries in Europe (Dias et al., 2007; Lewandowska et al., 2008; Schweinle and Thoroe, 1997; Seppala et al., 1998) as well as the USA (Gower et al., 2006; Johnson et al., 2005; O'Neil et al., 2010; Sonne, 2006; White et al., 2005). However, most previous forestry LCIs have focussed predominantly on greenhouse gas (GHG) balances, with little specific data on energy use and other inputs that could be used to assess other environmental impacts (e.g. Dias et al., 2007; Seppala et al., 1998; Sonne, 2006; White et al., 2005).

Life cycle inventories for wood production present a challenge because of the long time frames involved in the production process (the time from planting to harvesting can range from a decade to more than a century), the wide variety of operations included (e.g. site preparation, planting, road maintenance, fertiliser application, fire control, harvesting, extraction and haulage), the range of products generated (e.g. sawlogs of varying grades, posts, firewood,

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0378-1127/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2011.09.016

pulplogs and residues) and difficulty in quantifying non-wood values (biodiversity, tourism, water, etc.; Bosner and Porsinsky, 2008). Further, because tree growth rates, management systems and product characteristics are intrinsically related to the environmental conditions and locations in which forests grow, forestry LCIs can vary substantially for different regions, forest types and management objectives (e.g. Berg and Karjalainen, 2003; Dias et al., 2007; Lewandowska et al., 2008; Profft et al., 2009).

The development of a comprehensive LCI for forestry and forest products in Australia has been seen as a high priority for some years (Higham and Todd, 1998). Therefore, the aim of this study was to develop a CGI for forests in Australia used to produce solid wood products (e.g. sawn timber and engineered wood products). The Australian forestry industry is based on a mixture of native hardwood forests, and softwood and hardwood plantations. Solid wood products are primarily sourced from native forests and softwood plantations, while hardwood plantations are primarily grown for export woodchip (ABARE, 2010). Multiple use native forests, from which native hardwood logs are sourced, cover over 9 million ha and produce a total of 9 million m^3 logs annually, while softwood plantations occupy one million ha and produce 14 million m^3 $year^{-1}$ (ABARE, 2010). Hardwood plantations (mostly *Eucalyptus globulus* Labill.) planted over the past 12 years, occupy about the same area as softwood plantations, but currently produce just 5 million m^3 $year^{-1}$ although this amount is expected to increase substantially over the next 5 years as young plantations mature (Parsons et al., 2007). The present study includes only native hardwood forests and softwood plantations.

Undertaking a CGI for wood production in Australia has a number of unique challenges. These include the large range in climates, tree species and growth rates, and differing management priorities of the various Government agencies and private growers involved in forest management as well as the large number of private contractors involved in forest operations, harvesting and haulage. An important consideration is water-use by forests. In Australia, water is often a limiting factor for forest growth as well as for other uses. Thus, full assessment of environmental impacts of wood production should include accounting for evapo-transpiration (ET) or 'green water' use. However, quantifying the amount of water used is particularly difficult as there is no means to directly measure ET by forests across large areas. Further, the potential impact of water use depends on its origin (e.g. underground aquifers or soil moisture), relative abundance and level of competition for it between alternative land-uses, all of which are highly region-specific (Benyon et al., 2006; Hoekstra, 2009).

Most forestry LCIs have been limited to assessing inputs during growth and harvesting ('cradle-to-gate'; e.g. Johnson et al., 2005) although a few have attempted to follow the full life cycle of wood products ('cradle-to-grave'; e.g. Gower et al., 2006). The only published LCI of forestry in Australia is a partial assessment of primary energy inputs associated with growing and harvesting softwood plantations in one region of NSW, based on now outdated management and harvesting technologies (Wells, 1984). Here, we provide a CGI of inputs to native hardwood and plantation softwood forestry production in Australia from forest establishment to the delivery of logs and woodchips to processing facilities. The data are based on seven case studies from separate regions with major softwood plantations or native forests that are used for wood production. We estimate water use for both plantations and native forests and report on the direct inputs of natural resources (land, water), fuel (mainly diesel), fertiliser and other resources used in the forest production systems. The emissions from these inputs (CO_2 and non-CO_2 greenhouse gases and other emissions to air and water) are considered elsewhere (May et al., 2008; May et al., in preparation).

2. Materials and methods

2.1. Case studies

The inventory was based on seven case studies representative of the primary timber production regions for softwood plantations and hardwood native forests across Australia. The plantation softwood studies included the Green Triangle in south east Victoria and south west SA, Tumut in southern NSW, Fraser Coast in south-east Queensland and south west WA (Fig. 1). The native forest hardwood studies consisted of the Central Highlands in Victoria, central Tasmania and north east NSW (Fig. 1). Total annual log production for the four plantation softwood case studies was 7.0 million m^3 or 49% of mean annual softwood production across Australia for 2003–07, while total annual wood production for the three hardwood native forests case studies was 1.9 million m^3, representing 20% of total mean national production from these systems (ABARE, 2008: Table 2).

The geographic boundaries for the case study regions were based on those used in the National Plantation Inventory (Regions 3 and 4, Parsons et al., 2006) or local management areas (all others, Fig. 1). Data for each case study were sourced from local forest managers (e.g. forest areas, management inputs and wood production), forestry contractors (e.g. for fuel use during harvesting and haulage), or were derived from published studies (e.g. water use). To obtain a representative sample and preserve confidentiality of commercially-sensitive information, data from at least three contractors for each operation were aggregated for each case study region.

2.2. Production processes

The inventory covered wood production from seed/seedling to transport of logs and chips from the forest to processing facilities. The forestry system was divided into a sequence of four primary processes:

(i) Establishment: including production of seedlings in nurseries (plantations) or collection and processing of seed (native forests), site preparation (mechanical disturbance of sites and heaping of harvest slash), slash burning (burning of harvest residues), and planting (plantations) or aerial seeding or coppice management (native forests),
(ii) Management: including chemical application of herbicides or fertiliser (plantations only), fire prevention and control (fuel reduction burning, slashing and surveillance and control of wildfires) and roading (construction and maintenance of forest roads),
(iii) Harvest: including thinning (plantations only), final harvest (clear-felling or selective harvest of stands), and in-field chipping, and
(iv) Haulage: including transport of logs and chips from forest to processing facilities or ports.

Softwood plantations are grown in all states in Australia except the Northern Territory. The main species is *Pinus radiata*, with *Pinus pinaster* grown in drier regions in Western Australia and *Pinus caribaea* and *Pinus elliottii* grown in Queensland. Rotation lengths range from 25–35 years with between one and four thinnings prior to clearfelling. Site preparation is generally mechanical with residues mulched or, more rarely, heaped and burnt. Harvesting is usually by mechanical harvester with logs cut to length at stump and moved to the landing by forwarder, although in some situations (e.g. early thinnings) whole tree harvesting is practiced using a feller buncher and a skidder which snigs the harvested trees to a mobile chipper located at the landing. Transport of all harvested material is by road

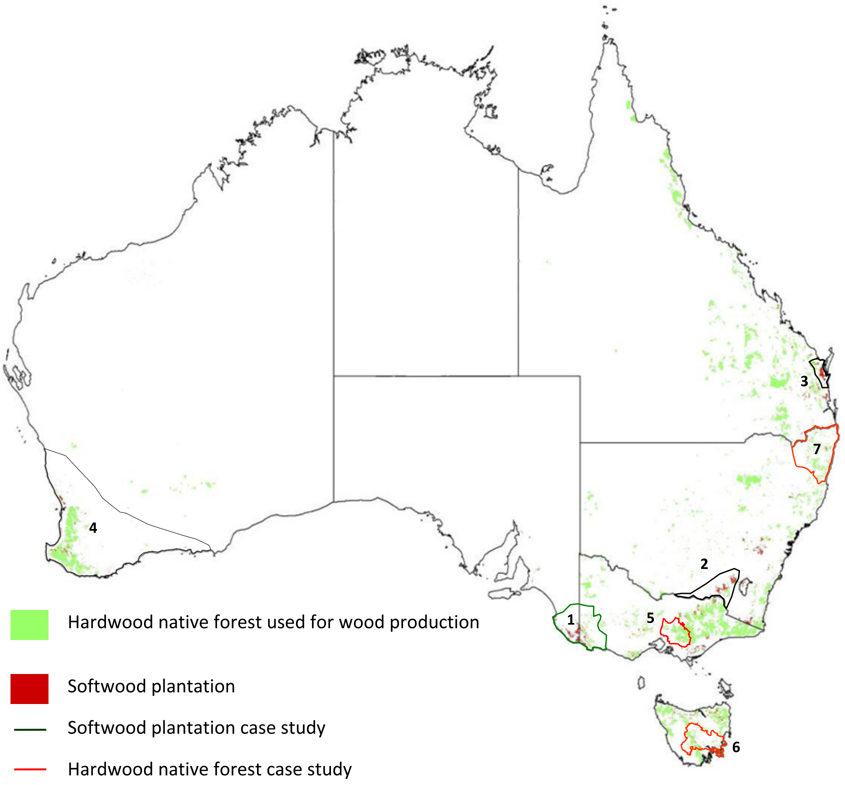
3
7
4
2
1
5
6
Hardwood native forest used for wood production
Softwood plantation
Softwood plantation case study
Hardwood native forest case study

Fig. 1. Location of Australian native forest used for wood production and softwood plantations, and the seven case study regions. 1 = Green Triangle in south west Victoria and south east SA, 2 = Tumut in southern NSW, 3 = Fraser Coast in south east Queensland, 4 = south west WA, 5 = Central Highlands in Victoria, 6 = central Tasmania and 7 = north east NSW.

using B-Doubles (consisting of a prime mover and two trailers with a total average max. load 45 t) for sawlogs and pulplogs and single semi-trailers (average max. load 25 t) for chips and other logs.

Native forests are managed for wood production in Victoria, NSW and Tasmania, with smaller areas in WA and Queensland. Across southern Australia, native forests are generally clearfelled after 60–100 years, while in northern NSW and Queensland they are selectively harvested to provide a mixed age class ranging from 0 to 125 years. After harvest, clearfelled stands are generally burnt to remove residues and create a seedbed, while selectively felled stands are mechanically disturbed. Native forests are re-established using aerial seeding or natural regeneration. The stands are generally left unthinned. Harvesting is usually mechanised, using feller buncher/skidder combinations although some hand felling is also practised. In steep terrain, cable logging is often used to winch logs to landings located on the tops of ridges. There is no onsite chipping of pulplogs in native forests. Log transport is by road using B-Doubles or Quad dogs (average max. load 33.5–38.5 t).

2.3. System boundary

The inventory was restricted to established forest land managed for wood production, and excluded new first-rotation plantings. In addition, inputs associated with the following processes or infrastructure were excluded: construction and operation of buildings and offices, manufacture of machines and vehicles used in forestry related activities; nursery operations associated with sale of seedlings to forest growers outside the study region; off-site processing of wood products including offsite chipping of logs; and inputs for which no data were available including paint, protective clothing, fuel or oil spillage.

Surveys provided data relating to direct inputs (those inputs under the direct control of the forest manager or forestry contractor) into the wood production process. Indirect inputs include energy and material use from upstream processes (e.g. energy consumed in mining, processing, manufacture or transport of fuel, fertiliser, steel or other materials used in the forestry process). In this paper, the only indirect input considered is energy use. This was estimated using the SimaPro (PRé Consultants, version 7.1) life cycle assessment model with the Australasian database (PRé, 2001; Life Cycle Strategies Pty Ltd. and Centre for Design at RMIT, 2010).

2.4. Sampling strategy and time period

The inventory aimed to quantify the average amounts of inputs and log removals from forests in each case study region for the period 2001–06. Thus, the sampling strategy aimed to cover a representative sample of forest growers and operators working in each region. For case studies in softwood plantations, four forest growers based in the Green Triangle and one grower in each of the three other regions were surveyed, covering ca. 90% of plantations by area in each region (Table 2). For case studies in hardwood native forest, three forest managers were surveyed (VicForests, Forests NSW and Forestry Tasmania) accounting for all the public native forest available for wood production in each region. Comparable overseas cradle-to-gate studies covering wood production from planting to delivery of logs to processing facilities indicate that the majority of energy use and greenhouse gas emissions are associated with harvesting and log transport (Johnson et al., 2005; Schweinle and Thoroe, 1997). Thus, sampling intensity was biased towards these operations while fewer contractors were surveyed for operations such as site preparation, road maintenance and fertiliser application. Wood production and operational data were obtained from forest managers and larger forestry contractors for the five-year period from 2001–02 to 2005–06. Smaller forestry contractors provided data on their operations for 2005–06 only.

2.5. Steady state of the forest production system

A key assumption of this study is that the forest production system is in a *steady state* both with respect to carbon stocks and management operations. This assumption has been used either explicitly or implicitly in most other forestry LCIs (e.g. Dias et al., 2007; Schweinle and Thoroe, 1997; Seppala et al., 1998; Sonne, 2006). It requires that there is no change in land use or management systems, forest biomass or productivity, soil organic matter stocks, or availability of nutrients and water over time at an estate level. Therefore, where possible, data for the native forest case studies were restricted to regrowth forest only (i.e. forest that had regenerated following either wildfire or timber harvesting within the past 100 years) and did not include the conversion of mature forest to regrowth forest. Since the area of softwood plantation in Australia is currently increasing by only a small amount each year (~1%) and the plantations in the case study regions are near to their maximum sustainable yield, they are close to satisfying the steady state assumption. Management and harvesting operations in both 1st and 2nd rotation stands were included, but establishment operations for new plantings on cleared agricultural land were excluded from the inventory.

2.6. Water use

Water use associated with wood production includes evapotranspiration (ET) across the forest estate (green water) as well as water used in irrigation of nurseries (blue water). The vast majority of water use in forestry is the former. To account for the fact that a proportion of this green water would be lost through ET regardless of whether the land was used for wood production, estimated water use by production forests was compared with that predicted for an alternative reference land-use. For plantations, grassland was considered to be an appropriate reference land-use. For native forests managed for wood production, unharvested forest reserved for conservation purposes was used as the reference. Net green water use was calculated as the difference between water use by the wood production forest and that of the reference land-use.

Total ET for softwood plantations or native hardwood forests for each case study region was estimated by applying a relationship between total rainfall and evaporation for forests developed by Zhang et al. (1999), across spatial (1 km resolution) surfaces of mean rainfall (ANUCLIM 5.1, McMahon et al., 1995) for the forested land managed for wood production (Montreal Process Implementation Group for Australia, 2008; Parsons et al., 2006). Water use for grassland was predicted for the same areas currently covered by softwood plantations by applying a relationship for grassland only (Zhang et al., 1999).

The relative difference between water use by native forest reserved for conservation purposes and those managed for wood production was estimated from published figures for ET for stands of varying ages and assumed maximum stand ages. Estimates of the change in ET with stand age were based on figures from long-term catchment studies in the Victorian Central Highlands (Moran and O'Shaughnessy, 1984; Vertessy et al., 2001). No long-term data were available for tall open forests in Tasmania or NE NSW. However, one study covering the first 16 years of regeneration from NE NSW (Cornish and Vertessy, 2001) indicated that the change in water use with stand age for these forests followed a similar trend to those in Victoria, so the relative change in water use over time reported by Vertessy et al. (2001) was used as the basis for estimating average water use in other native forest regions.

The average rotation length of a harvested native forest in each region was assumed to be 80 years while the average period between natural disturbance (by wildfire) of an unharvested forest was assumed to average 250 years based on an average fire return time of 100–350 years in tall open forests (Ashton, 1976; Attiwill, 1994; Lindenmayer, 2009). If the regrowth forest is at steady state and the rotation length is 80 years, then that forest will contain a mixture of ages after earlier harvests. Similarly, if an unharvested forest is assumed to be burnt every 250 years, then it too can be considered to include a mixture of age classes ranging from 0 to 250 years. Therefore, we calculated the average ET over the 80 year rotation to estimate average water use for the regrowth forest and over 250 years to estimate average water use by an unharvested forest. Based on data from Vertessy et al. (2001), mean ET for a stand with a maximum age of 250 years (1100 mm year^{-1}) was estimated to be 14% less than that of a stand with a maximum age of 80 years (1280 mm year^{-1}) in a catchment with a mean annual rainfall of 1800 mm. Thus, it was assumed that ET from a forest reserved for conservation purposes would be 14% less than that for a harvested forest estimated from the relationship developed by Zhang et al. (1999, 2001).

2.7. Wood products

Products from both softwood plantations and hardwood native forests were divided into four categories: large sawlogs, small sawlogs, pulplogs and other logs (Table 1). The latter included softwood logs (used for preservation treatment) and hardwood logs (used for posts, piles and girders). A fifth product (in-forest chips) from softwood plantations accounted for woodchips produced by mobile chippers located in the forest in conjunction with some forest operations (e.g. whole tree harvesting or residue removal).

Table 1

Product names, descriptions and values used for economic allocation of emissions in the softwood plantation and native forest hardwood case studies. Products and prices adapted from KPMG (2007; 5 year weighted average) for softwood, and from information provided by forest managers for hardwood products.

Forest and log type	Description	Value ($ m^{-3})
Plantation softwood		
Large sawlog	Large sawlogs and peeler logs with SED $\geqslant$320 mm	69
Small sawlog	Small sawlogs with SED <320 mm	40
Pulplog	Logs suitable for woodchips or pulp	10
In-forest woodchips	Pulplogs chipped in forest prior to haulage	10
Other log	Posts for treatment	21
Native forest hardwood		
Large sawlog	Large sawlogs and veneer logs used for high-value products	47
Small sawlog	Small or low-value sawlogs used for structural timber	15
Pulplog	Logs suitable for woodchips or pulp	13
Other log	High quality logs suitable for posts, poles and girders	131

SED: small end diameter.

Table 2
Major species, mean wood density, and wood production (2003–07) from softwood plantations and hardwood native forests comprising the different case study regions. The broader forest regions represented by the case studies and the proportion of total production represented (regional coverage) is also summarized.

Forest type and case study region				Representative region of Australia			Regional coverage (%)
Region	Species	Wood density (kg m^{-3})	Production (000 m^3 $year^{-1}$)	Region	Production (000 m^3 $year^{-1}$)	Proportion of total (%)	
Plantation softwood							
Green Triangle	*P. radiata*	440	3534	Vic., SA, Tas.	7567	52	47
Tumut, NSW	*P. radiata*	440	1489	NSW, ACT	3591	25	41
SE Qld.	*P. caribaea*, *P. elliotii*	480	1124	Qld., NT	2334	16	48
SW WA	*P. radiata*, *P. pinaster*	450	857	WA	934	6	92
Total		447	7005		14426	100	49
Hardwood native forest							
Vic. Central Highlands	*E. regnans*, *E. delegatensis*	510	867	Vic., Sth. NSW, WA	3434	37	25
Central Tas.	*E. obliqua*, *E. delegatensis*, *E. regnans*	560	229	Tas.	4495	49	2
NE NSW	*E. pilularis*, *C. maculata*, *E. saligna*	710	758	Nth. NSW, Qld.	1330	14	57
Total		595	1853		9260	100	20

Vic.: Victoria, SA: South Australia, NSW: New South Wales, Tas.: Tasmania, ACT: Australian Capital Territory, Qld: Queensland, NT: Northern territory, WA: Western Australia.

Pulplogs from hardwood native forests included some logs classed as ‘peeler logs’, but which were sold for a similar value to pulplogs.

Non-wood forest products and values such as water yield, biodiversity and tourism were not included because of the difficulty in applying economic values to these. Thus, even though management for non-wood products and services from native forests, in particular, requires substantial resources as well as careful controls over wood production activities, here we assumed that wood was the primary product of both native forests and plantations.

2.8. Wood density and energy content

Dry density of the wood was estimated based on data from Ilic et al. (2000) for representative species from each region (Table 2). These data were assumed to represent the density of sawlogs. Density of pulplogs and chips harvested from softwood plantations was assumed to be 10% lower than that of sawlogs, while density of other logs harvested from softwood plantations was assumed to be 20% lower than that of sawlogs based on information from forest managers (Nethercott, Auspine; Watt, Forests NSW, *pers. comm.*) and published reports showing age-related trends in density of trees from softwood plantations in the Green Triangle and WA (Blakemore et al., 2010; Roper et al., 2004). We could not source data for differences among densities of products from native forests, so pulplogs and other logs were assumed to have densities similar to that of sawlogs. For both plantation softwood and native hardwood forests, an overall mean density (D) for log type a (Da) was weighted by mean production of each log type from each case study as follows:

$$Da = (D_1 \times Pa_1 + D_2 \times Pa_2 + \ldots + Dn \times Pan)/(Ptot) \tag{1}$$

where Dn is the mean density of the logs produced in case study n, Pan is the mean production of log type a represented by case study n and $Ptot$ is the total log production for all the case studies.

Published figures for the Gross Calorific Value (GCV) of the softwood species covered in the study (*P. radiata*, *P. elliottii* and *P. pinaster*) range from 20.0 to 21.4 MJ kg^{-1} on a dry basis (mean 20.6 MJ kg^{-1}) while published figures for eucalypt species range from 19.0 to 20.2 MJ kg^{-1} (mean 19.6 MJ kg^{-1}; Nunez-Regueira et al., 1999; Perez et al., 2008; Pierre et al., 2011; Senelwa and Sims, 1999; Ye et al., 2003). Net Calorific Value (NCV, which includes the energy used to evaporate water) for wood combusted in a dry environment can be calculated from the following formula:

$$\mathrm{NCV} = \mathrm{GCV} - 2.442(\mathrm{MC}/100 - 9 \times \mathrm{H}/100) \tag{2}$$

where MC is the % moisture content of the wood (expressed on a wet basis) and H is its % hydrogen content (Perez et al., 2008).

Based on results from Ximenes et al. (2008) it was assumed that the moisture content of the harvested logs and chips was about 50% while the average percentage hydrogen in both *P. radiata* and *E. globulus* about 6% (Nunez-Regueira et al., 1999). Thus, the mean NCVs of logs and chips at downstream processing facilities were estimated to be 18 MJ kg^{-1} (dry weight) for plantation softwood and 17 MJ kg^{-1} (dry weight) for native hardwood. The NCV for each species and log type was calculated on a volumetric basis (i.e. MJ m^{-3}) using the estimated basic densities.

2.9. Data aggregation

Data were collected from all major forest owners/managers and a sample of forestry contractors for each case study region. Data were expressed in terms of the unit of production from the particular operation (e.g. area of land burnt or ripped for site establishment, or volume of wood for harvesting and transportation operations) and were weighted with respect to the relative proportions of total production attributed to each operator for each region.

For log transportation, mean distance, load weight and consumption of fuel and materials were collected for different product types from each operator. Total fuel or material use for each company was then calculated as follows:

$$T_{ilc} = A_{ic} \times D_c \times 2/L_c \tag{3}$$

where T is the average amount of fuel or other input (i) consumed per m^3 of wood for each log type (l) and contractor (c), A is the average amount of the input consumed per km, D is the average haulage distance (one way) and L is the average load size expressed in m^3.

For each case study region, means for individual log transport companies were weighted by the total amount of each product transported. Survey coverage for each process and sub-process was estimated from the proportion of total production contributed by each particular forest owner serviced by the contractor surveyed. Weighting and coverage of other operations in each region were estimated from the area or distance covered by each contractor operation (e.g. total distance of road maintained in the reference year). Where these data were not available, data were weighted by the relative amount paid by the forest owner to each contractor.

To estimate average national figures for softwood plantations and hardwood native forests, results for the case studies were weighted according to the proportion of total production of specific log types (for in-field chipping and haulage) or proportion of total wood production (all other operations) represented by each case study region (Table 2).

Results for individual case studies and the national averages were expressed in terms of unit wood production and were broken down by operation (e.g. establishment, fire control, roading, harvest and haulage). This provided a total for each input or emission per m^3 log produced as well as the contributions of individual forestry operations.

Indirect energy use associated with upstream processes such as manufacture of fuel and materials (e.g. diesel production, fertiliser manufacture and steel production) were estimated using the Australasian database of SimaPro by linking machinery, fuel and material use from each of the four processes in each forestry system to existing processes in the database (PRé, 2001; Life Cycle Strategies Pty Ltd. and Centre for Design at RMIT, 2010).

2.10. Allocation to products

Inputs to the forestry process, up to and including harvest, were allocated to products (sawlogs, pulplogs and chips) on an economic basis. Values for plantation softwood products were estimated from the Australian pine log price index (KPMG, 2007) based on a five-year weighted average price (2001–06, Table 1). Values for native forest products were based on average prices provided by individual forest growers (Table 1). Downstream processes such as in-field chipping and transport of products to processing facilities were allocated to the specific products being chipped or transported.

The general formula used to allocate the total amount of particular input, I, to a specific product, a, was:

$$I_a = V_aS_a/(V_tS_t)^*If + Ic_a + It_a \quad (4)$$

where I_a is the total amount of a particular input allocated to product a, V_a is the total volume of product a, S_a is the stumpage value of product a, V_t is the total volume of all products, S_t is the weighted average stumpage value of all products, If is the total amount of the input used from seedling production up to and including final harvest of the forest, Ic_a is the amount of the input associated with chipping product a (in-field chips only) and It_a is amount of the input associated with transport of the product.

3. Results

3.1. Resources used for timber production

3.1.1. Land

Land use per unit wood production for softwood plantations, as estimated from the total plantation area and the total annual volume harvested, varied from 0.05 ha year m^{-3} in the Green Triangle to 0.10 ha year m^{-3} in WA, with a mean of 0.06 ha year m^{-3} (Table 3). These figures are equivalent to mean rates of wood production ranging from 10 m^3 ha^{-1} $year^{-1}$ in WA to 20 m^3 ha^{-1} $year^{-1}$ in the Green Triangle (mean: 17 m^3 ha^{-1} $year^{-1}$; data not shown).

By comparison, land use per unit wood production for hardwood native forests, ranged from 0.11 ha year m^{-3} in the Victorian Central Highlands to 0.98 ha year m^{-3} in the selectively logged NE NSW forests and averaged 0.28 ha year m^{-3} (Table 4). This is

Table 3
Summary of direct inputs used in the production of plantation softwood logs for each of the three case study regions, and the national average. Indirect energy inputs refer to upstream energy used to produce materials used in forest management (see Section 2 for details).

Item		Unit	Case study				Mean	SD
			Green triangle	Tumut	SE Qld	WA		
Natural resources								
Land		ha year m^{-3}	0.05	0.06	0.08	0.10	0.06	0.02
Water		ML m^{-3}	0.07	0.15	0.23	0.17	0.12	0.07
Energy								
Diesel	Volume	L m^{-3}	4.3	3.3	6.8	4.6	4.4	1.5
	Energy	MJ m^{-3}	164	126	262	179	172	57
Aviation fuel	Volume	L m^{-3}	0.04	0.02	0.02	0.03	0.03	0.01
	Energy	MJ m^{-3}	1.4	0.8	0.6	1.0	1.1	0.3
Direct energy		MJ m^{-3}	166	126	263	180	173	57
Indirect energy		MJ m^{-3}	202	69	191	120	120	63
Total energy		MJ m^{-3}	367	195	454	300	293	109
Materials								
Lubricant		L m^{-3}	0.08	0.07	0.12	0.08	0.08	0.02
Tyres		kg m^{-3}	0.05	0.04	0.09	0.05	0.05	0.02
Steel		kg m^{-3}	0.09	0.06	0.08	0.09	0.08	0.02
Gravel		kg m^{-3}	340	694	640	192	467	240
Bitumen		kg m^{-3}	0.0	0.4	0.0	0.0	0.1	0.2
Fertiliser (macro elements only)								
N		kg m^{-3}	0.57	0.002	0.04	0.02	0.30	0.27
P		kg m^{-3}	0.35	0.003	0.11	0.01	0.20	0.16
K		kg m^{-3}	0.09	0.000	0.08	0.00	0.06	0.05
S		kg m^{-3}	0.45	0.001	0.00	0.02	0.24	0.22
Herbicide (by active ingredient)								
Atrazine		g m^{-3}	7.3	6.1	0.0	9.9	6.0	4.2
Glyphosate		g m^{-3}	1.1	4.8	11.4	1.7	3.8	4.7
Simazine		g m^{-3}	0.0	0.0	19.2	0.0	3.1	9.6
Hexazinone		g m^{-3}	3.2	2.3	0.0	0.6	2.3	1.5
Triclopyr		g m^{-3}	0.0	0.0	1.4	0.0	0.2	0.7
Other		g m^{-3}	0.4	0.1	1.0	1.1	0.4	0.5
Fungicide		g m^{-3}	0.06	0.00	0.00	0.04	0.03	0.03

Qld: Queensland, WA: Western Australia, SD: standard deviation.

Table 4
Summary of direct inputs used in the production of native hardwood logs for each of the three case study regions, and the national average. Indirect energy inputs refer to upstream energy used to produce materials used in forest management (see Section 2 for details).

Item		Unit	Case study			Mean	SD
			Vic CH	Tasmania	NE NSW		
Natural resources							
Land		ha year m^{-3}	0.11	0.21	0.98	0.28	0.48
Water		ML m^{-3}	0.16	0.27	1.31	0.38	0.64
Energy							
Diesel	Volume	L m^{-3}	8.5	9.2	11.1	9.2	1.3
	Energy	MJ m^{-3}	330	352	429	355	52
Aviation fuel	Volume	L m^{-3}	0.1	0.1	0.0	0.1	0.0
	Energy	MJ m^{-3}	2.7	2.1	0.8	2.2	1.0
Electricity		MJ m^{-3}	0.27	0.15	0.00	0.17	0.13
Gas		MJ m^{-3}	0.77	0.00	0.00	0.29	0.45
Direct energy		MJ m^{-3}	333	354	430	357	51
Indirect energy		MJ m^{-3}	168	163	234	170	39
Total energy		MJ m^{-3}	501	517	663	527	89
Materials							
Lubricant		L m^{-3}	0.17	0.29	0.21	0.13	0.06
Tyres		kg m^{-3}	0.09	0.07	0.20	0.07	0.07
Steel		kg m^{-3}	0.14	0.28	0.10	0.10	0.09
Gravel		kg m^{-3}	472	156	45	257	222

Vic CH: Victorian Central Highlands, NSW: New South Wales, SD: standard deviation.

equivalent to rates of wood production of 1–9 m^3 ha^{-1} $year^{-1}$ (mean: 3.5 m^3 ha^{-1} $year^{-1}$; data not shown).

3.1.2. Fuel and energy

Direct energy use (mostly in the form of diesel) per unit wood production averaged 173 and 357 MJ m^{-3} for softwood plantations and hardwood native forests, respectively (Tables 3 and 4). The greater amount of fuel and energy inputs associated with production of native hardwood logs was largely due to fuel use in harvesting (4.5 vs. 1.9 L m^{-3}) and haulage (3.8 vs. 2.1 L m^{-3}; data not shown).

For both forest types, there was large variation in direct energy use among case studies. This variation was largely due to differences in fuel consumption during harvesting (1.2–2.1 L m^{-3} for softwood plantations and 3.3–5.5 L m^{-3} for hardwood native forests) and haulage (1.5–4.0 L m^{-3} for softwood plantations and 3.0–5.0 L m^{-3} for hardwood native forests, data not shown). These two processes were the major contributors to direct energy inputs, accounting for 88% of the total for softwood plantations and 90% for hardwood native forests.

Mean indirect energy use was 29% less for softwood plantations (120 MJ m^{-3}) than for hardwood native forests (167 MJ m^{-3}; Tables 3 and 4). Again, there was marked variation among the individual case studies. In softwood plantations, this variation was mainly related to differences in fertiliser use which accounted for 37% of total indirect energy use in the Green Triangle, but just 5% for WA. For native forests, variation in indirect energy use was mainly associated with differences in fuel and machinery use in haulage and forest management.

Mean total energy use was 45% less in softwood plantations (293 MJ m^{-3}) than in hardwood native forests (525 MJ m^{-3}, Table 3 and Table 4). Major contributors to total energy used in production of plantation softwood logs included haulage (45%), harvesting (24%), fertiliser (15%) and in-field chipping (5%), with other processes comprising 11% (Fig. 2a). For logs from native forests, major contributors to total energy use included haulage (45%), harvesting (44%) and road construction and maintenance (8%), with other operations contributing just 4% (Fig. 2b).

3.1.3. Chemicals and materials used

More chemicals and materials were used in softwood plantations compared with native forests. Significant amounts of N and P fertiliser were applied to softwood plantations although the amounts used varied greatly from region to region (Table 3). Other major nutrients applied included S and K. The most common fertiliser forms used were triple superphosphate, ammonium sulphate, urea and potassium sulphate. Herbicides were also widely used across softwood plantations. The most commonly used included atrazine, glyphosate, simazine and hexazinone.

Other material inputs in softwood plantations were mostly associated with machinery maintenance. These included lubricants (0.08 L m^{-3}), tyres (0.05 kg m^{-3}) and steel for replacement parts including machine tracks, chainsaw blades and chains (0.08 kg m^{-3}). In addition, a mean of 467 kg m^{-3} gravel was used in road construction and maintenance (Table 3).

There was no use of herbicides or fertilisers in native hardwood forests. However, use of lubricants (0.13 L m^{-3}), tyres (0.07 kg m^{-3}) and steel for machine tracks, chainsaw blades and chains (0.11 kg m^{-3}) were all greater than that in softwood plantations (Table 4). The amount of gravel used in constructing and maintaining roads (257 kg m^{-3}) was about 60% of that used in softwood plantations. However, there was very large variation in gravel use between the different case studies for each forest type (Tables 3 and 4).

3.1.4. Water

For the softwood plantations, annual rainfall ranged from 740 mm in the Green Triangle to 1310 mm in south-east Queensland (mean 960 mm) and estimated annual ET ranged from 670 to 1010 mm (mean 800 mm; Table 5). Thus, in terms of total wood production, forest ET ranged from 0.33 to 0.79 ML m^{-3} (mean 0.49 ML m^{-3}). However, relative to ET from grassland, net water-use ranged from 130 to 300 mm (mean 200 mm) or 0.07 to 0.23 ML m^{-3} (mean 0.12 ML m^{-3}).

For hardwood native forests, annual rainfall ranged from 1210 mm in central Tasmania to 1420 mm in the Victorian Central Highlands (mean 1270 mm) and estimated annual ET ranged from 940 to 1050 mm (mean 980 mm; Table 5). Because of the large differences in wood production per unit area, variation in total water use per volume of wood extracted was greater than that for per hectare water use, ranging from 1.2 ML m^{-3} in the Victorian Central Highlands to 9.6 ML m^{-3} in north east NSW (mean 2.8 ML m^{-3}). Based on the estimated 14% reduction in ET as a result of the assumed increase in maximum stand age if the forests were

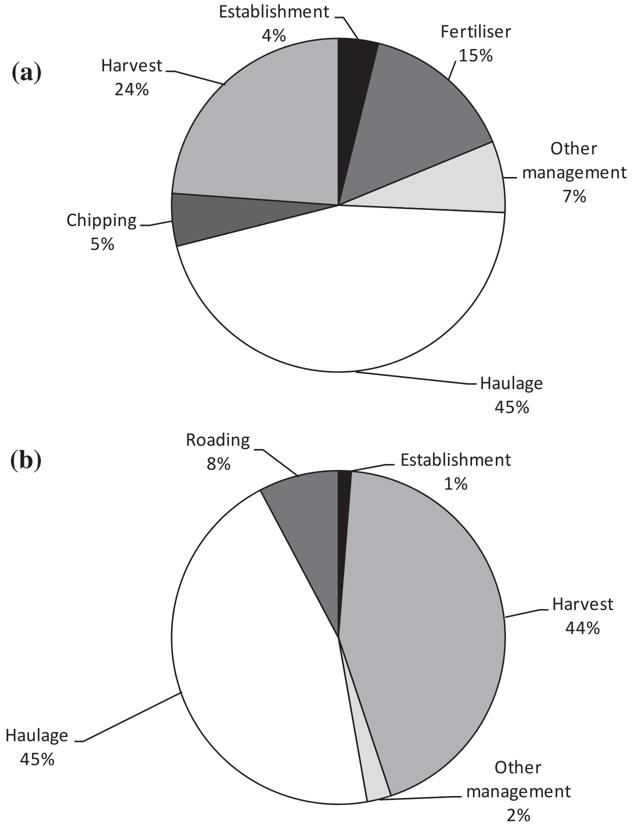

Fig. 2. Relative contributions of different forest management operations to total energy use in wood production from: (a) softwood plantation (total = 293 MJ m^{-3}) and (b) hardwood native forest (total = 527 MJ m^{-3}).

reserved from timber harvesting, relative water use was estimated to be 130–140 mm greater than that if the forests were reserved for conservation. Thus, in terms of the additional amount of water used for wood production, mean net water use associated with production of native hardwood logs was 0.2–1.3 ML m^{-3} (mean 0.38 ML m^{-3}).

The only use of 'blue water' in either forest type was associated with irrigation of plantation softwood seedlings in nurseries. However, this usage was negligible in terms of the amount used per unit wood produced (0.1 kL m^{-3}).

3.2. Allocation to products

Under an economic allocation methodology, products from the same process with a higher unit value have a proportionally greater amount of inputs allocated. Thus, for softwood plantations, allocation of land varied from 0.02 ha year m^{-3} for pulplogs and chips to 0.11 ha year m^{-3} for high-value sawlogs (Table 6). Similarly, fuel allocations varied from 2.2 L m^{-3} for pulplogs to 6.1 L m^{-3} for high-value sawlogs, while total energy use varied from 130 MJ m^{-3} for pulplogs to 387 MJ m^{-3} for high value sawlogs. In-field chips had the largest fuel use and second largest total energy use as a result of the relatively energy intensive nature of chipping operations which consumed about 3 L diesel m^{-3}.

For products from hardwood native forests, the largest proportion of inputs was allocated to other logs (posts, piles and girders) as these had the highest value, while the lowest proportion was allocated to pulplogs (Table 7). However, the former represent only 1.5% of the total value of wood production in Australian hardwood forests and 0.2% of the total volume. Excluding these relatively minor products, allocation of land ranged from 0.18 ha year m^{-3} for pulplogs to 0.65 ha year m^{-3} for high value sawlogs, and total energy use ranged from 388 MJ m^{-3} for pulplogs to 857 MJ m^{-3} for high-value sawlogs.

3.3. Energy balance

Mean estimated net energy content based on estimated dry densities and an assumed Net Calorific Value of 18 MJ kg^{-1} (dry weight) for plantation softwood and 17 MJ kg^{-1} (dry weight) for native hardwood was 7.4 and 8.5 GJ m^{-3} for plantation softwood and native hardwood logs, respectively (Table 8). In terms of energy balance, the total energy consumed in growing, harvesting and transporting an average log represented just 3.8% of the energy content of an average plantation softwood log (range 1.8–4.9%) and 5.8% of that of an average native hardwood log (range 4.3–17.0%).

4. Discussion

4.1. Comparison between forest types and case studies

In general, the amounts of inputs associated with a unit of wood production were greater for native forests than for softwood plantations. For example, an average log produced from native forests required five times more land, eleven times more water, twice as

Table 5
Predicted evapotranspiration (ET) for each case study region based on annual rainfall and the relationship developed by Zhang et al. (2001) for forests. Means are weighted by total production (for water use per unit production) or land area (for total rainfall and ET).

Case study	Forest			Rainfall	Evapotranspiration			Water use	
	Area	Annual wood production		Mean	Forest[1]	Reference[2]	Difference	Absolute[3]	Relative[4]
	(000 ha)	(000 m^3 $year^{-1}$)	(m^3 ha^{-1} $year^{-1}$)	(mm $year^{-1}$)	(mm)	(mm)	(mm)	(ML m^{-3})	(ML m^{-3})
Softwood plantation									
Green Triangle	176	3534	20	738	665	534	131	0.33	0.07
Tumut, NSW	90	1489	17	1125	911	666	245	0.55	0.15
SE Qld.	87	1124	13	1314	1012	716	296	0.79	0.23
SW WA	85	857	10	866	752	582	170	0.74	0.17
Mean			17	957	802	607	195	0.49	0.12
Hardwood native forest									
Vic. CH	84	758	9	1421	1053	909	144	1.2	0.16
Central Tas.	182	867	5	1207	939	811	129	2.0	0.27
NE NSW	224	229	1	1263	978	844	134	9.6	1.31
Mean			4	1270	977	843	134	2.8	0.38

Vic CH: Victorian Central Highlands, NSW: New South Wales, Tas.: Tasmania, Qld: Queensland, WA: Western Australia.
[1] Total ET from forests estimated from annual rainfall and relationship between rainfall and ET for forests in equilibrium (Zhang et al., 2001).
[2] Reference land use assumed to be pasture for plantations and unlogged native forest for native forest.
[3] Total ET from forests divided by total wood extracted.
[4] Difference in ET from forests relative to that for reference land-use divided by total wood extracted.

Table 6
Allocation of inputs to different plantation softwood log types. Allocations are based on economic value of products. Indirect energy inputs refer to upstream energy used to produce materials used in forest management (see Section 2 for details).

Item		Unit	Sawlog		Pulplog	Chips	Other log
			High value	Low value			
Natural resources							
Land		ha year m^{-3}	0.11	0.06	0.02	0.02	0.03
Water		ML m^{-3}	0.22	0.13	0.03	0.03	0.07
Energy							
Diesel	Volume	L m^{-3}	6.1	4.4	2.2	6.9	4.3
	Energy	MJ m^{-3}	235	169	83	266	165
Aviation fuel	Volume	L m^{-3}	0.06	0.03	0.01	0.01	0.02
	Energy	MJ m^{-3}	2.0	1.2	0.3	0.3	0.6
Direct energy		MJ m^{-3}	237	171	83	266	166
Indirect energy		MJ m^{-3}	143	96	46	85	65
Total energy		MJ m^{-3}	380	267	129	350	230
Materials							
Lubricant		L m^{-3}	0.13	0.08	0.03	0.06	0.06
Tyres		kg m^{-3}	0.07	0.06	0.03	0.06	0.06
Steel		kg m^{-3}	0.12	0.07	0.02	0.25	0.04
Gravel		kg m^{-3}	861	495	118	118	266
Bitumen		kg m^{-3}	0.18	0.11	0.03	0.03	0.06
Fertiliser (macro elements only)							
N		kg m^{-3}	0.56	0.32	0.08	0.08	0.17
P		kg m^{-3}	0.37	0.21	0.05	0.05	0.12
K		kg m^{-3}	0.11	0.07	0.02	0.02	0.04
S		kg m^{-3}	0.44	0.25	0.06	0.06	0.13
Herbicide (by active ingredient)							
Atrazine		g m^{-3}	11.0	6.3	1.5	1.5	3.4
Glyphosate		g m^{-3}	6.9	4.0	1.0	1.0	2.1
Simazine		g m^{-3}	5.7	3.3	0.8	0.8	1.8
Hexazinone		g m^{-3}	4.2	2.4	0.6	0.6	1.3
Triclopyr		g m^{-3}	0.4	0.2	0.1	0.1	0.1
Other		g m^{-3}	1.2	0.7	0.2	0.2	0.4
Fungicide		g m^{-3}	0.06	0.04	0.01	0.01	0.02

Table 7
Allocation of inputs to different native hardwood log products. Allocations are based on economic value of products. Indirect energy inputs refer to upstream energy used to produce materials used in forest management (see Section 2 for details).

Item		Unit	Sawlog		Veneer log	Pulplog	Other log
			High value	Low value			
Natural resources							
Land		ha year m^{-3}	0.65	0.21	1.00	0.18	1.81
Water		ML m^{-3}	0.87	0.28	1.33	0.24	2.41
Energy							
Diesel	Volume	L m^{-3}	16.1	7.9	22.7	7.3	38.3
	Energy	MJ m^{-3}	616	303	872	281	1470
Aviation fuel	Volume	L m^{-3}	0.1	0.0	0.2	0.0	0.4
	Energy	MJ m^{-3}	4.8	1.6	7.7	1.4	14.5
Electricity		MJ m^{-3}	0.39	0.13	0.60	0.11	1.09
Gas		MJ m^{-3}	0.64	0.21	1.01	0.18	1.9
Direct energy		MJ m^{-3}	622	304	882	282	1485
Indirect energy		MJ m^{-3}	240	149	362	107	569
Total energy		MJ m^{-3}	862	453	1244	389	2055
Materials							
Lubricant		L m^{-3}	0.24	0.12	0.36	0.09	0.64
Tyres		kg m^{-3}	0.07	0.07	0.06	0.07	0.08
Steel		kg m^{-3}	0.24	0.08	0.36	0.06	0.66
Gravel		kg m^{-3}	572	188	904	164	1710

much fuel, 50% more lubricant and 30% more steel and rubber (in tyres). These differences were partly due to the differences in productivity rates between plantations and native forests as well as more difficult terrain and longer haulage distances for the latter. However, they also reflect differences in management objectives; native forests are managed for a wide range of values including biodiversity, recreation and water supply while plantations are managed almost solely for wood production. As a result of the different management objectives, rotation lengths are longer and the proportion of non-merchantable trees is much greater in native forests, reducing the effective extraction rate of merchantable wood per unit land area compared with plantations. As a result, the allocation of land, water and, to a lesser extent, fuel and consumables was greater for wood from native forests than from plantations.

In contrast to direct energy use, indirect energy use in hardwood native forests was only 41% greater than that in softwood plantations, largely due to differences in chemical inputs (Tables

Table 8
Average estimated dry density, energy content and energy consumed during production, harvest and transport of different logs from softwood plantations and hardwood native forests.

	Density ($kg\ m^{-3}$)		Gross energy content ($GJ\ m^{-3}$)		Fossil energy consumed ($GJ\ m^{-3}$)		Net energy content ($GJ\ m^{-3}$)		Embodied energy (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Plantation softwood										
Sawlogs										
High value	442	18	7.9	0.3	0.38	0.12	7.6	0.2	4.8	1.3
Low value	449	18	8.1	0.3	0.27	0.08	7.8	0.2	3.3	0.9
Pulplogs	401	17	7.2	0.3	0.13	0.04	7.1	0.2	1.8	0.5
Woodchips	396	7	7.1	0.1	0.35	0.04	6.8	0.2	4.9	0.6
Other logs	391	15	6.5	0.3	0.23	0.07	6.3	0.2	3.5	1.0
Wtd. average	429	19	7.7	0.3	0.29	0.09	7.4	0.2	3.8	1.0
Native hardwood										
Sawlogs										
High value	581	102	9.9	1.7	0.86	0.15	9.0	1.6	8.7	0.3
Low value	626	102	10.6	1.7	0.45	0.08	10.2	1.7	4.3	0.1
Pulplogs	494	91	8.4	1.6	0.39	0.07	8.0	1.5	4.6	0.1
Other logs	710	NA	12.1	NA	2.05	NA	10.0	NA	17.0	NA
Wtd. Average	530	119	9.0	2.0	0.53	0.09	8.5	1.9	5.8	0.3

3 and 4). Fertilisers and herbicides used in softwood plantations comprised 36% of the average indirect energy inputs as a result of the substantial amounts of energy used in their production. For example, synthesizing of ammonia typically consumes 25–35 GJ t^{-1} ammonia (30–43 GJ t^{-1} N; Wood and Cowie, 2004). In our study, the Ecoinvent database was used to estimate energy use associated with fertiliser production and transport based on information from the European Fertilizer Manufacturers Association (e.g. EFMA, 2000a, 2000b). Energy use associated with nitrogen fertiliser ranged from 55 GJ t^{-1} N for urea to 143 GJ t^{-1} N for ammonium sulphate, while that for phosphorus fertiliser ranged from 52 GJ t^{-1} P for triple super phosphate to 124 GJ t^{-1} P for diammonium phosphate. Thus, the increase in the efficiency of wood production resulting from fertiliser application must be balanced with the increased energy cost of the fertiliser used.

In contrast, most indirect energy use for hardwood native forests was associated with harvesting (56 MJ m^{-3} or 33% of the total) and haulage (89 MJ m^{-3} or 53% of the total, data not shown). This was mainly a result of upstream production of fuel, steel and tyres used by machinery and trucks.

As well as differences between forest types, there was large variation in inputs and energy use between case study regions. For example, land and water use in the Green Triangle were 17% and 45% less respectively compared with the average for softwood case studies (Table 3). These differences may reflect the long history of genetic improvement, nutrient management and optimisation of silviculture in this region (e.g. Boardman, 1979; Carlyle and Nambiar, 2001; May et al., 2009a; Wu et al., 2007). In contrast, the relatively low management intensity of the native forests of north east NSW, including selective harvesting and limited pulplog removal (comprising just 9% of total production compared with 60–85% of total production for the two other native forest case studies), resulted in relatively low rates of log production per unit land occupied or water consumed (Table 4).

4.2. Wood energy balance

The energy balances clearly show that total energy inputs represent only a small proportion of the gross energy content of logs and woodchips harvested from both Australian softwood plantations (mean 4%) or hardwood native forests (6%; Table 8). Thus, the amount of non-renewable energy used in their production and transport to sawmills and woodchip processing facilities (i.e. embodied energy) is only a fraction of the renewable energy (derived from photosynthesis) content of the logs themselves. This result is consistent with results from other studies which indicate that energy associated with forestry production comprises around 2–5% of the total energy content of the logs (Berg and Lindholm, 2005; Hodgson et al., 2006; Johnson et al., 2005; Schweinle and Thoroe, 1997). This high ratio of renewable energy content to embodied energy makes logs and woodchips potentially useful for reducing embodied energy in potential downstream applications (e.g. by using wood residues from sawmilling for heat production during kiln drying of timber) and a potential source of renewable energy.

The energy content of wood is largely dependent on its assumed dry density which varies with age and log type as well as species and location (Table 2). Further, ultimate embodied energy of wood products will depend on downstream energy use in processing and the recovery of marketable products (eg. sawn timber) while a complete LCI of energy consumption should include energy use associated with using and disposing of the materials. Thus, the total embodied energy in finished products such as kiln-dried sawn timber, particleboard or biofuel will be greater than that in the raw logs (see Tucker et al., 2009). However, this cradle to gate inventory provides a basis for estimating total embodied energy and net energy content of wood products from Australian softwood plantations and native forests by quantifying the embodied energy of the raw material (i.e. logs). Linking appropriate log types with their respective downstream stages of the life cycle will allow total embodied energy and other inputs to these products to be assessed.

4.3. Water use

Relative to ET from alternative land uses (i.e. pasture for softwood plantations and conservation reserves for native forest), the additional water use associated with wood production was equivalent to 0.12 ML m^{-3} for softwood plantations and 0.38 ML m^{-3} for native forests. These estimates are based on limited data and should be considered as indicative only, especially for native forests. However, the fact that wood production is excluded from many forested water catchments in Victoria, partly as a result of concerns over potential impacts on water supply, is consistent with this result (Poynter and Featherston, 2008).

The estimated relative change in water use with forest age used in our study was largely based on results from Vertessy et al. (2001) in one of the case study regions. Further long-term measurements of changes in evapo-transpiration over time in other regions with differing rainfall and species are needed to confirm the assumption that water use of unharvested native forests is roughly 14% less than that of harvested native forests. Recent work in

Table 9
Comparison of direct energy (MJ m^{-3}) in forestry operations in Australia derived from the current study compared with that for other studies in Australia and overseas.

Operation	Australia				NZ	USA		Sweden	Portugal		Spain	Germany
	Native hardwood	Plantation softwood			Plantation softwood	Native softwood Pacific NW	Plantation softwood South East	Plantation softwood	Eucalypt plantation	Softwood plantation	Eucalypt plantation	Mixed[4]
	Mean	Mean	Tumut	Tumut								
	This study	This study	This study	Wells (1984)	Hodgson et al. (2006)[1]	Johnson et al. (2005)		Berg and Lindholm (2005)[2]	Dias et al. (2007)[3]		Gonzalez-Garcia et al. (2009)	Schweinle (1997)[5]
Seed/seedling production	0.8	0.4	0.4	0.2	NA	NA	NA	7.7	NA	NA	NA	NA
Establishment	3.0	7.7	6.4	10.1	NA	NA	NA	8.6	47.2	33.1	30	7.7
Management	31	12	15	19	NA	20	22	3	57	45	83	6
Harvest												
Thinning	0	29	15	NA	NA	19	32	NA	NA	NA	NA	90
Clearfell	174	36	33	NA	NA	96	86	NA	64	NA	155	118
Chipping	0.0	8.1	0.0	0.0	NA	NA	NA	NA	NA	NA	NA	NA
Total	174	73	47	146	NA	115	118	63	64	57	155	208
Total ex. haulage	209	93	69	175	92	135	140	82	169	135	269	221
Haulage	148	80	58	NA	273	162	213	96	NA	NA	124	123
Total	358	173	126	NA	365	297	354	178	NA	NA	393	345

NA: no data available.

[1] Based on direct energy usage of 1.43 PJ year^{-1} for forestry operations and 4.26 PJ year^{-1} for transport, and an annual wood harvest of 15.6 million m^3 year^{-1}.

[2] Mean of figures for forestry operations in the northern, central and southern regions.

[3] Estimated from published CO_2 emissions.

[4] Beech, oak, spruce and pine.

[5] Includes indirect energy use associated with upstream production and transport of inputs which is estimated to account for around 35% of total energy use. Data converted from MJ t^{-1} to MJ m^{-3} by assuming an average dry density of wood of 0.5 t m^3.

Victorian water catchments has resulted in the development of a site-specific water yield model (Watson et al., 1999) that overcomes many of the limitations associated with the more generalised Kuczera Curve (Kuczera 1985). This Macaque hydrological model (Watson et al., 1999) is providing more precise estimates of the effect of different forest management scenarios on water yields. Initial results from this work are consistent with those from the current study, indicating that excluding timber harvesting altogether from forested water catchments could be expected to result in a gradual increase in water yields over 25 years (Battad et al., 2007).

Wood production may reduce the effective amount of available water for other purposes such as irrigation and municipal water supply. However, this opportunity cost must be weighed against benefits in terms of reduced potential for transfer of nutrients to rivers and aquifers and reduced soil erosion for forests compared with agriculture (Larned et al., 2004; May et al., 2009b; Quinn and Stroud, 2002).

There was minimal use of surface water or underground aquifers (blue water) in softwood plantations and no use of blue water in hardwood native forests. For softwood plantations, a small amount of irrigation was used during seedling production averaging 58 ML million seedlings^{-1} or 0.1 kL m^{-3} wood harvested. There is evidence that some softwood plantations may draw water directly from underground aquifers in regions where water tables are high (<2 m below the surface) and there is no impeding layer (Benyon et al., 2006). However, this may occur at only some locations in the Green Triangle region, and thus is expected to affect only a small proportion of the total area covered by softwood plantations in Australia.

4.4. Comparison with other studies on energy and fuel use for timber production

Apart from being the first comprehensive CGI for Australian forestry production, this is the first to include detailed information on land, water, fertiliser or other non-energy inputs used in the forestry production system. Furthermore, this study is the most comprehensive yet published in terms of accounting for both direct and indirect energy use for forestry. Most published forestry CGIs have focussed on greenhouse gas emissions and either do not report energy use or include only fuel consumption (e.g. Berg and Karjalainen, 2003; Dias et al., 2007; Johnson et al., 2005; Paul et al., 2006; Schwaiger and Zimmer, 2001; Sonne, 2006; White et al., 2005). Other studies provide detailed information on consumption of natural resources (e.g. oil, gas, coal) and emission of gases (e.g. CO_2, SO_2, N_2O, etc.), heavy metals and nutrients, but no information on energy use or contributions of different processes (e.g. Seppala et al., 1998). Those studies which have explicitly included energy (e.g. Berg and Lindholm, 2005; Gonzalez-Garcia et al., 2009; Schweinle and Thoroe, 1997) do not provide a breakdown between direct and indirect energy consumption. Only the assessment of energy use by the forest sector in New Zealand by Hodgson et al. (2006) provides such a breakdown, but this is based on a top-down approach (i.e. estimates are based on input output tables which relate economic data from the industry as a whole to energy usage) and is not strictly comparable to the bottom-up approach (i.e. based on direct surveys of energy and input usage) used in most LCIs. Further, it has been noted that there is little consistency in system boundaries and methodology used in the various studies (Karjalainen et al., 2001). For example, some studies include seedling production or haulages in the forest system boundary (e.g. Berg and Lindholm, 2005) while others exclude them (e.g. Dias et al., 2007). There are major differences in both the methodology for estimation of energy associated with upstream processes (e.g. Gonzalez-Garcia et al., 2009; Wells, 1984) and the upstream processes that are included (e.g. Berg and Lindholm, 2005; Schweinle and Thoroe, 1997).

Despite these differences, we can still obtain an indication of relative energy efficiency of Australian forestry operations by comparing direct energy use across studies (Table 9). Our results indicate that energy used for current softwood timber production in the Tumut region is lower than that reported for production over 30 years ago (Wells, 1984). This difference is likely to be due to improvements in fuel efficiency and forest productivity over time.

For example, total fuel use in harvesting plantation softwood logs was estimated to be 146 MJ m^{-3} in this earlier study, compared with just 47 MJ m^{-3} in 2006–07 (Table 9). Comparison with overseas studies indicates that wood production from Australian softwood plantations is also relatively energy efficient by world standards (Table 9). Total direct energy use for operations excluding haulage was lower than other studies, with the exception of those for New Zealand and Sweden. Further, when haulage was included, direct energy use in Australian softwood plantations was lower than for the NZ and Swedish studies, and between 42% and 56% less than for the other studies. The reasons for the relatively low energy use in Australian softwood plantations include less energy use in establishment and management compared with plantations in Spain and Portugal, more efficient harvesting compared with operations in the USA and Spain and lower fuel consumption during haulage compared with all other published studies (Table 9).

In contrast to softwood plantations, direct energy usage in Australian hardwood native forests was close to the upper limit for overseas studies (Table 9). Excluding haulage, only wood production from short rotation hardwood plantations in Spain and native forests in Germany required more energy per unit wood harvested. The relatively high energy consumption for Australian native forests was almost entirely due to higher fuel use during harvesting operations, which is likely to reflect the dispersed nature of harvesting operations, and rigorous environmental guidelines applied. In contrast, energy consumption during haulage was within the range for the other studies.

4.5. Limitations of this study

A key assumption of our study was that the forest was in a steady state. This implies that the rate of wood production was relatively constant over time and could be related to the level of energy and other inputs used in establishment and management. This assumption is not strictly correct for plantations because the area of softwood is slowly expanding over time. However, this rate of expansion is relatively slow (ca. 1% per year) and Australian softwood plantations are close to their sustainable yield in terms of wood production. Further, only replanted areas were included in the forest establishment process, and management inputs across the total estate were relatively minor in terms of total energy use compared with other processes such as harvesting and haulage which were based on the actual area of forest estate harvested. For native forests, conversion of mature forest to regrowth was excluded from our study. Further, regrowth forests were created progressively, mostly over the last 70 years following either wildfire or harvesting and regeneration activities. Thus, the steady state assumption is considered reasonable for both softwood plantations and native forests.

Two other key assumptions were that: (a) forest management data collected from managers and contractors were representative of the whole case study region and that (b) the study region was broadly representative of the portion of national wood production allocated to it. These assumptions are considered reasonable for plantation softwood because a large proportion of each region's production and operations were covered in the surveys and because almost 50% of total national softwood production was included in the four case studies. Further, plantation softwood production systems are relatively similar across the country, and differences due to climate, species and silviculture were covered in the case studies selected. However, for native forests, only a relatively small proportion of national production was included in the three case study regions (20%). Furthermore, survey coverage within each region was suboptimal, and for some regions information had to be based on unpublished estimates from forest management agencies. There was wide variation in land, water and energy use between the three case studies and data for some processes (e.g. fuel used in log haulage) were relatively poor. Thus, estimates for logs from native hardwood forest reported here have higher uncertainty than those for softwood plantations.

Estimates of the energy content of wood included a number of important assumptions. These included: (a) the mean density of the species surveyed being equal to means reported by Ilic et al. (2000), (b) the density of different products varying by an assumed percentage from that mean and (c) the Net Calorific Value for plantation softwood and native hardwood logs being 18 and 17 GJ t^{-1}, respectively. However, there are no published data on the variation in wood density of different log types from Australian softwood plantations or native forests. Instead, differences in density of different log types were based on the 'expert opinion' of local forest managers. Thus, estimated energy contents of the different log types are subject to considerable uncertainty (perhaps ±0.8–1.0 GJ m^{-3}) much larger than the estimated amount of energy consumed during forestry production process for most products (Table 8).

An important exclusion from our study was wood produced from hardwood plantations in Australia. Hardwood plantations supplied wood volumes in excess of 4 million m^3 $year^{-1}$ (16% of total production) in 2009–10 and are expected to increase to 20 million m^3 $year^{-1}$ by 2010–15 (ABARE, 2010; Parsons et al., 2006). These plantations were not included because: (a) they did not fit the steady state assumption (i.e. the amount of wood currently being harvested is far lower than the potential sustainable yield based on the area currently being planted and managed) and (b) most of the material produced is exported as wood chips and thus not used by downstream processing industries in Australia.

This is the first published life cycle inventory of forestry to attempt to include water use. Although the models used to estimate water use are applicable to most sustainably managed forests and plantations across the world (Zhang et al., 2001), they do not take into account factors such as varying rotation lengths, fallow periods, access to groundwater and management intensity which may increase or decrease water use (Benyon et al., 2006). Further, while the relative water use of plantations was based on the difference in ET for forests compared with grassland as modelled by Zhang et al. (2001), relative water use of native forests was based on the relative difference in ET for forests with different maximum ages (i.e. 80 years for forests managed for wood production c.v. 250 years for forests managed for conservation purposes) estimated by integrating a long-term forest water use curve (Vertessy et al., 2001). It is difficult to assess the range of error that might be expected from using this methodology. Ongoing research in the measurement and modelling of water use by these forests will help provide more accurate estimates of the relative impact of wood production from native forests on water availability (e.g. Battad et al., 2007).

4.6. Conclusion

This study provides the first CGIs of inputs into wood production from forests in Australia. Unlike most published forestry LCIs we provide a breakdown of inputs across different log types using an economic basis for allocation. This is also the first forestry CGI to include an estimation of "green water" use associated with wood production and to provide a method to assess the relative impact of this use compared with alternative land uses. Our results show that direct energy use for logs produced in Australian softwood plantations is among the lowest in the world, while that for hardwood native forests is high relative to many other published studies. Total fossil energy consumed in the production, harvest and haulage of logs represented only a small fraction of the energy contained in logs from both forest types. This is useful both for estimating the embodied energy of downstream wood products, as well as potential energy return from using low value logs and residues for bioenergy. Future improvements to our LCI include better estimates of water and energy use in transport of native hardwood logs, and the inclusion of other forest types (e.g. hardwood plantations). The LCI presented here provides the basis for building comprehensive LCIs for most wood products produced in Australia.

Acknowledgements

The authors thank Forests and Wood Products Australia for partly funding this study, which formed part of a wider wood products LCI study undertaken by CSIRO and RMIT. Substantial assistance both in provision of data and review of results was provided by forest owners and managers from the seven case study regions. In addition, a wide range of contractors involved in harvesting, haulage, site preparation, spraying and fire control provided detailed data on their operations. From CSIRO, Selwyn Tucker and Mike Syme provided valuable advice on the overall methodology, Nico Marcar assisted with data collection and editorial comments, Randall Falkiner assisted with data collection and Richard Benyon provided valuable advice on forest water use.

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